High-Energy Nuclear Collisions and the QCD Phase Structure

-- Recent Results from STAR Experiment

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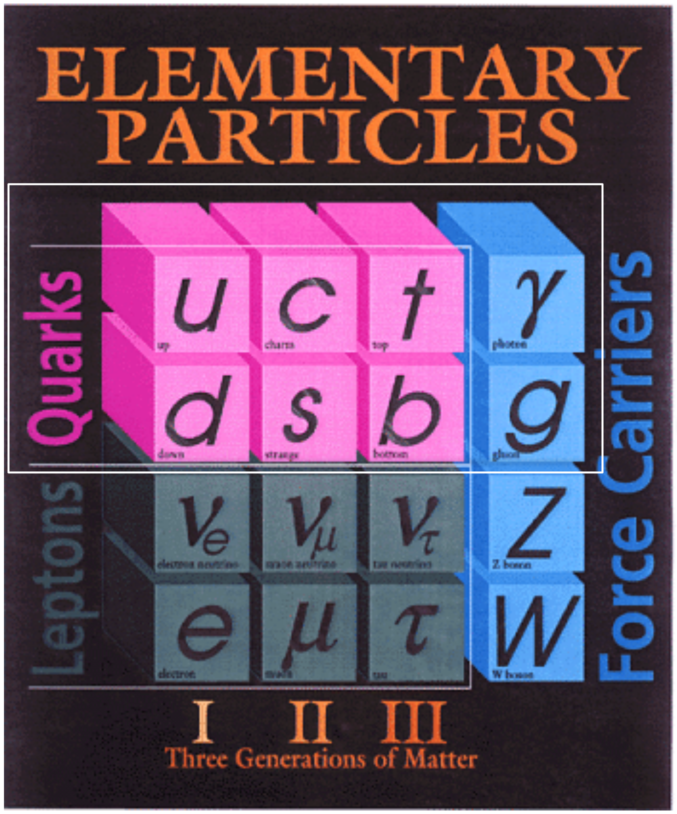
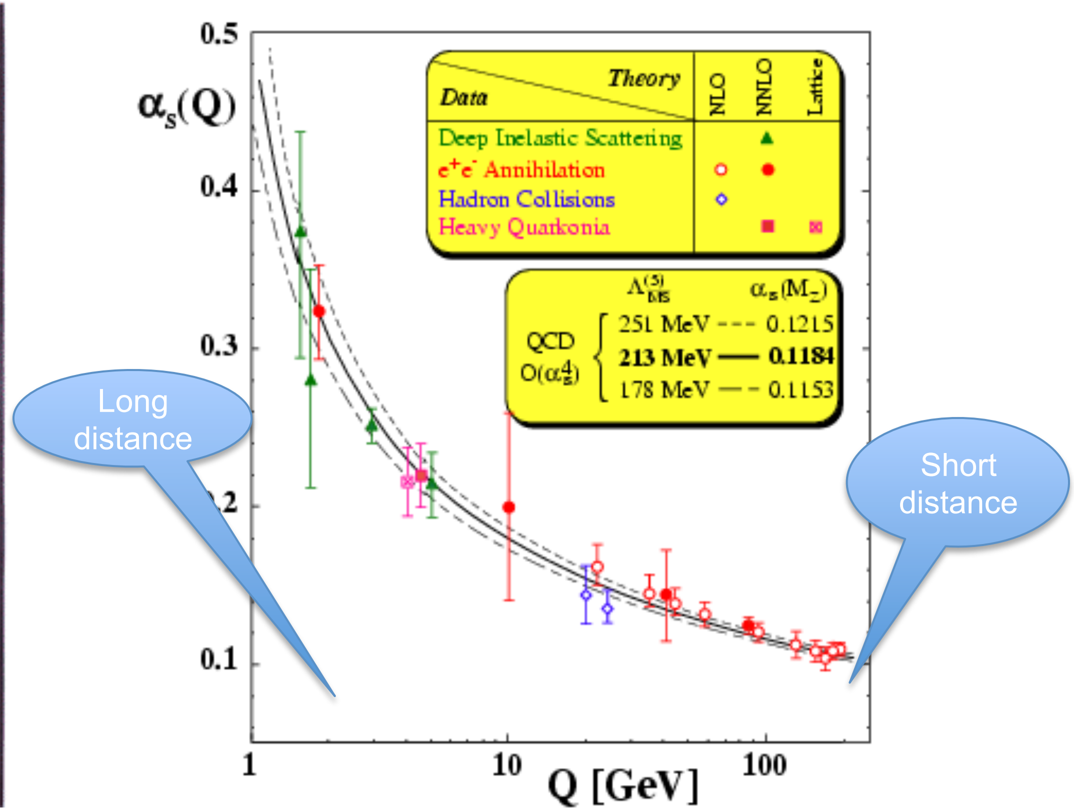
Many Thanks to the Organizers!

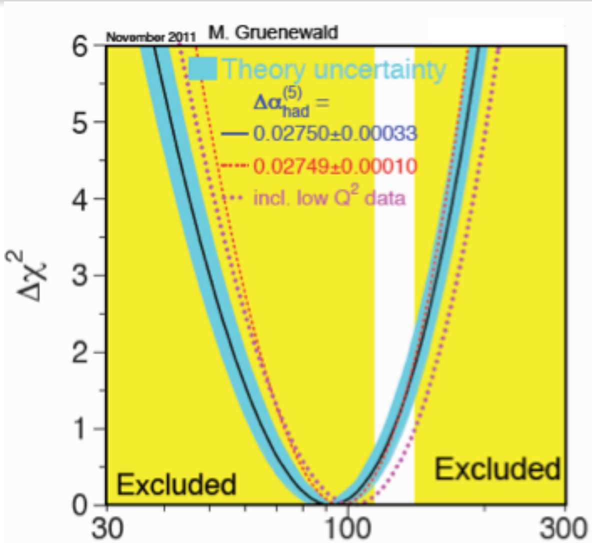
Quantum ChromoDynamics

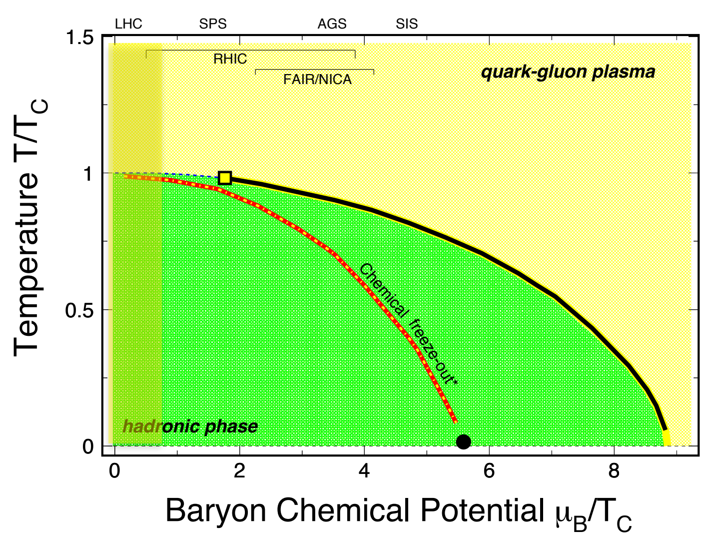




1) QCD is the basic theory for strong interaction. Its degrees of freedom are well defined at short distance.
2) Little is known regarding the dynamical structures of matter that made from ***q, g***. *E.g. the confinement*, *nucleon spin*, the ***QCD phase structure***... Large $\boldsymbol{\alpha_s}$ and strong coupling – QCD at long distance.

QCD in Twenty-One Century

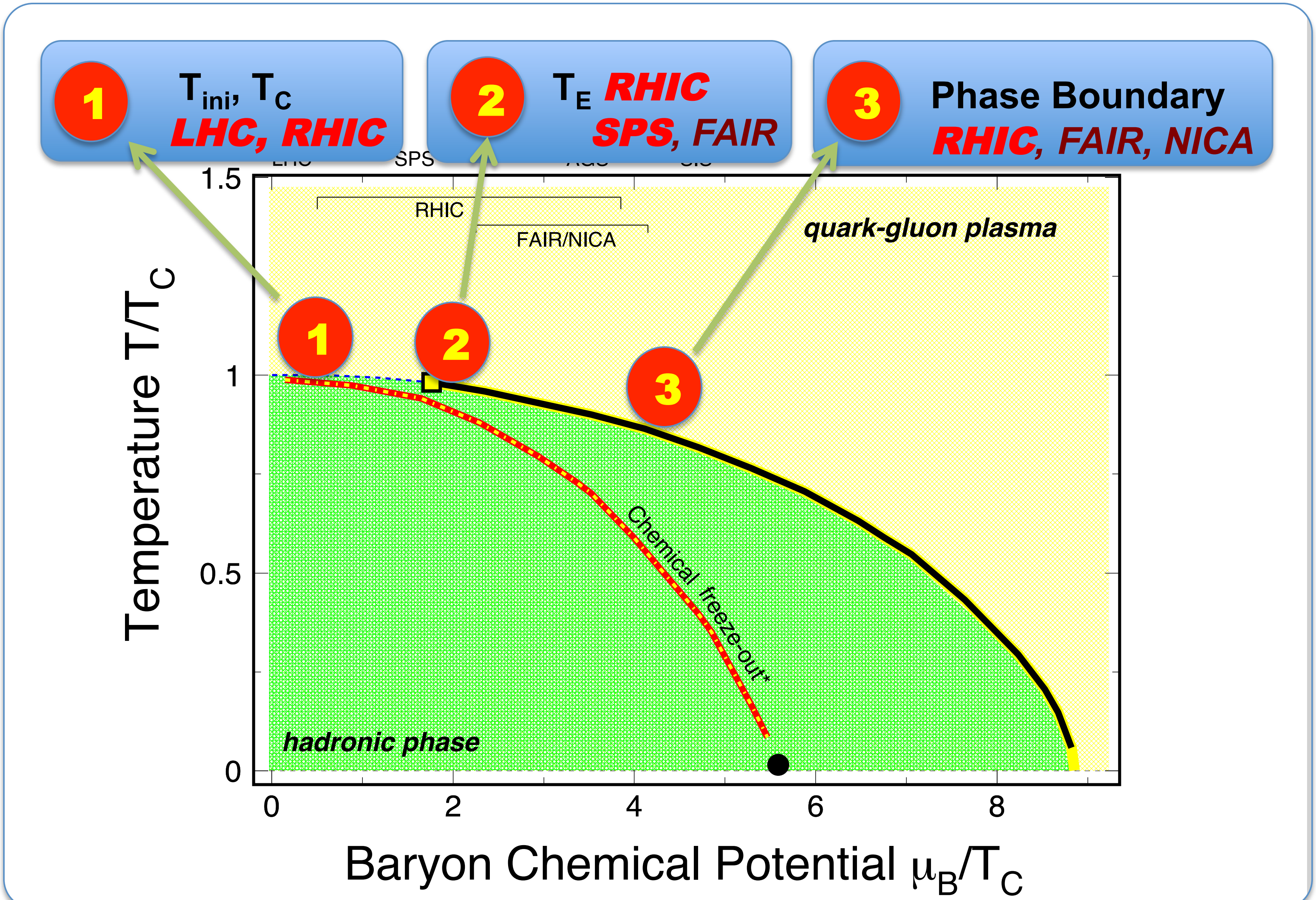




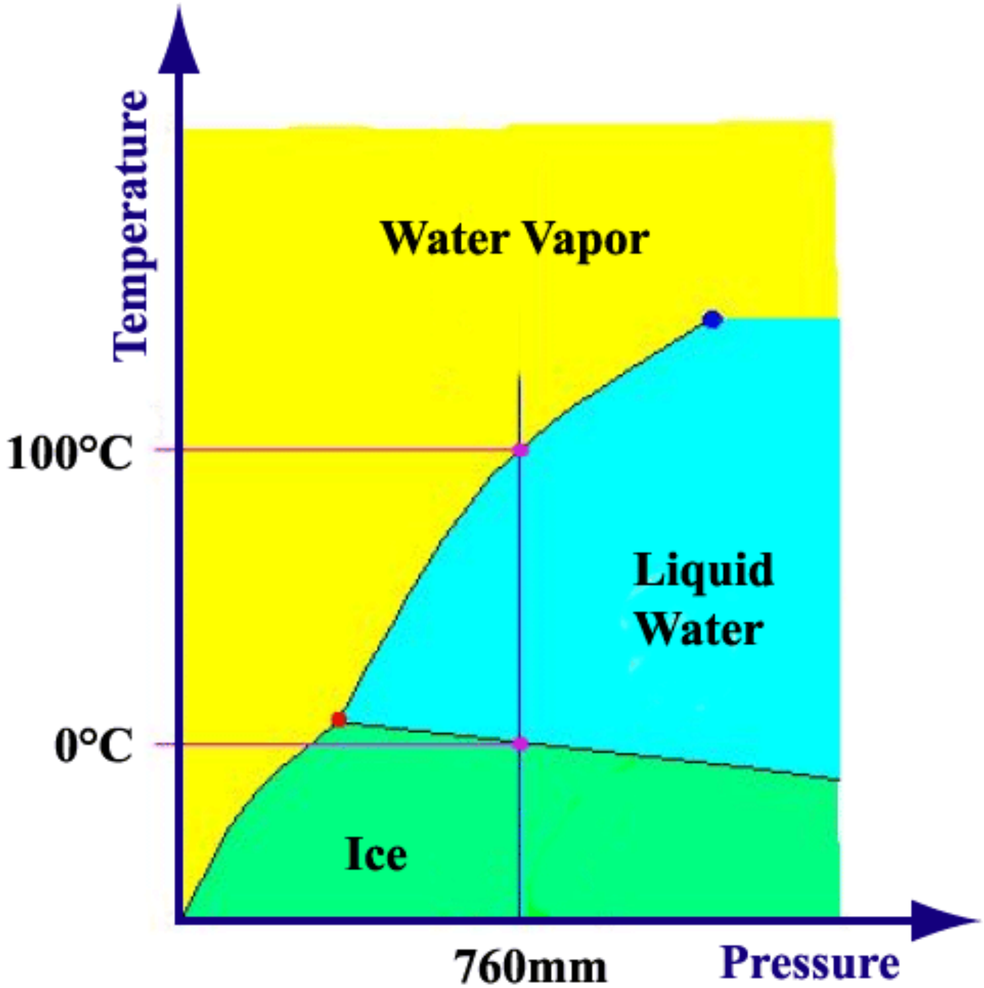
(1) Higgs Particle –
- Origin of Mass
- S.M. ➔ The *Theory*

(2) QCD Phase Structure –
- Critical point, phase boundaries
- Confinement
- χ_C symmetry
- Nucleon helicity structure
- …
- Non-linear QCD
- …
- Emerging properties
- …
- String theory

The QCD Phase Diagram and High-Energy Nuclear Collisions



Phase Diagram: Water



Phase diagram: A map shows that, at given degrees of freedom, how matter organize itself under external conditions.

Water: H_2O

The QCD phase diagram: structure of matter with quark- and gluon-degrees (color degrees) of freedom.

Outline

(1) Introduction

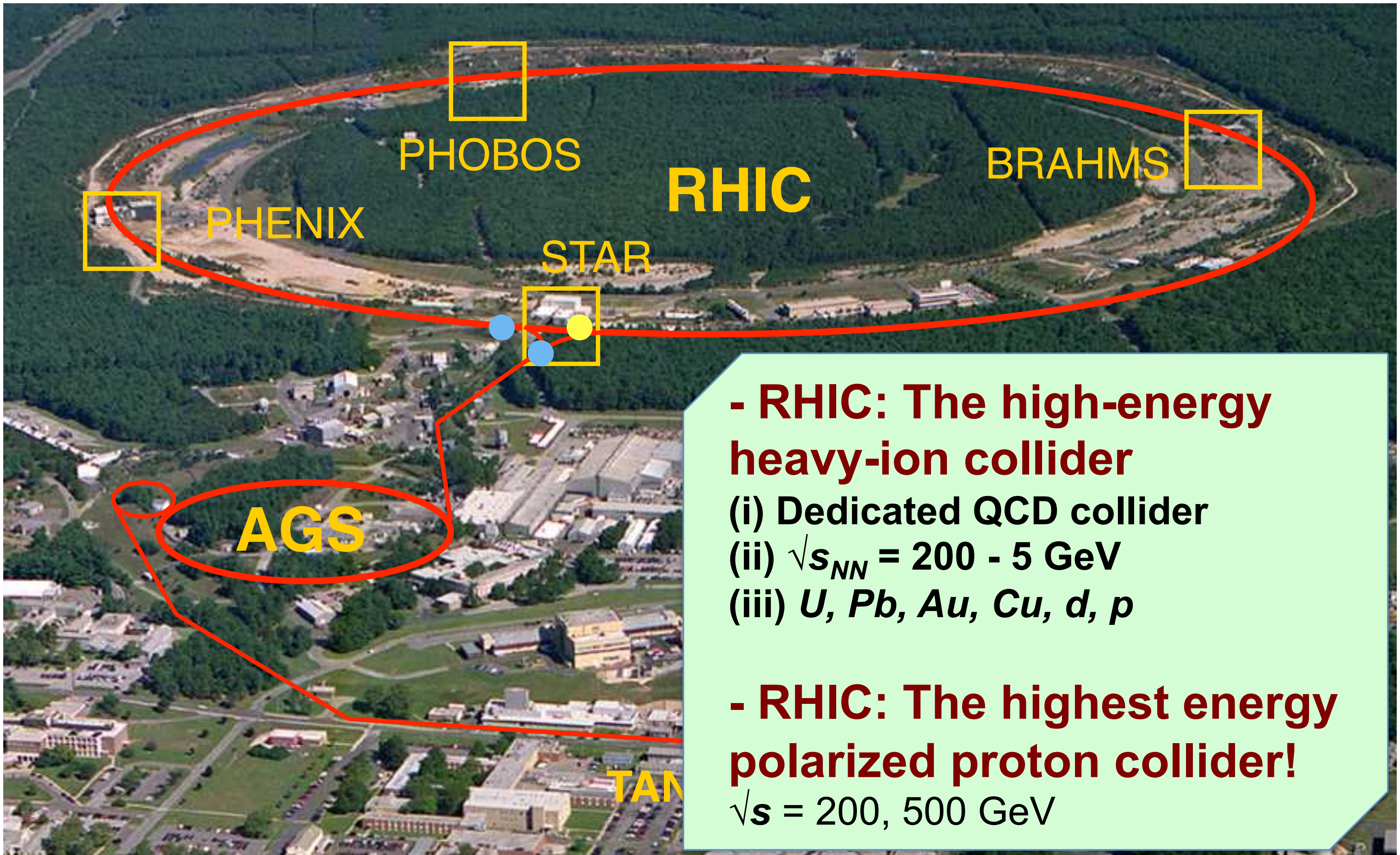
(2) New from of Matter at RHIC

(3) RHIC Beam Energy Scan

(4) Summary and Outlook

Relativistic Heavy Ion Collider

Brookhaven National Laboratory (BNL), Upton, NY



- **RHIC: The high-energy heavy-ion collider**
  (i) Dedicated QCD collider
  (ii) $\sqrt{s_{NN}}$ = 200 - 5 GeV
  (iii) *U, Pb, Au, Cu, d, p*

- **RHIC: The highest energy polarized proton collider!**
  $\sqrt{s}$ = 200, 500 GeV

Animation M. Lisa

STAR Collaboration

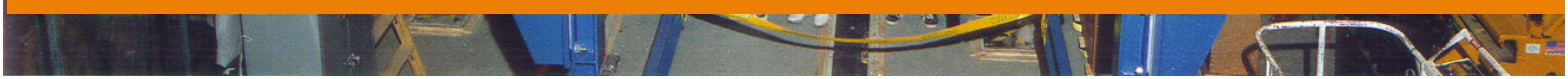
STAR Experiment at RHIC

(http://www.star.bnl.gov/)

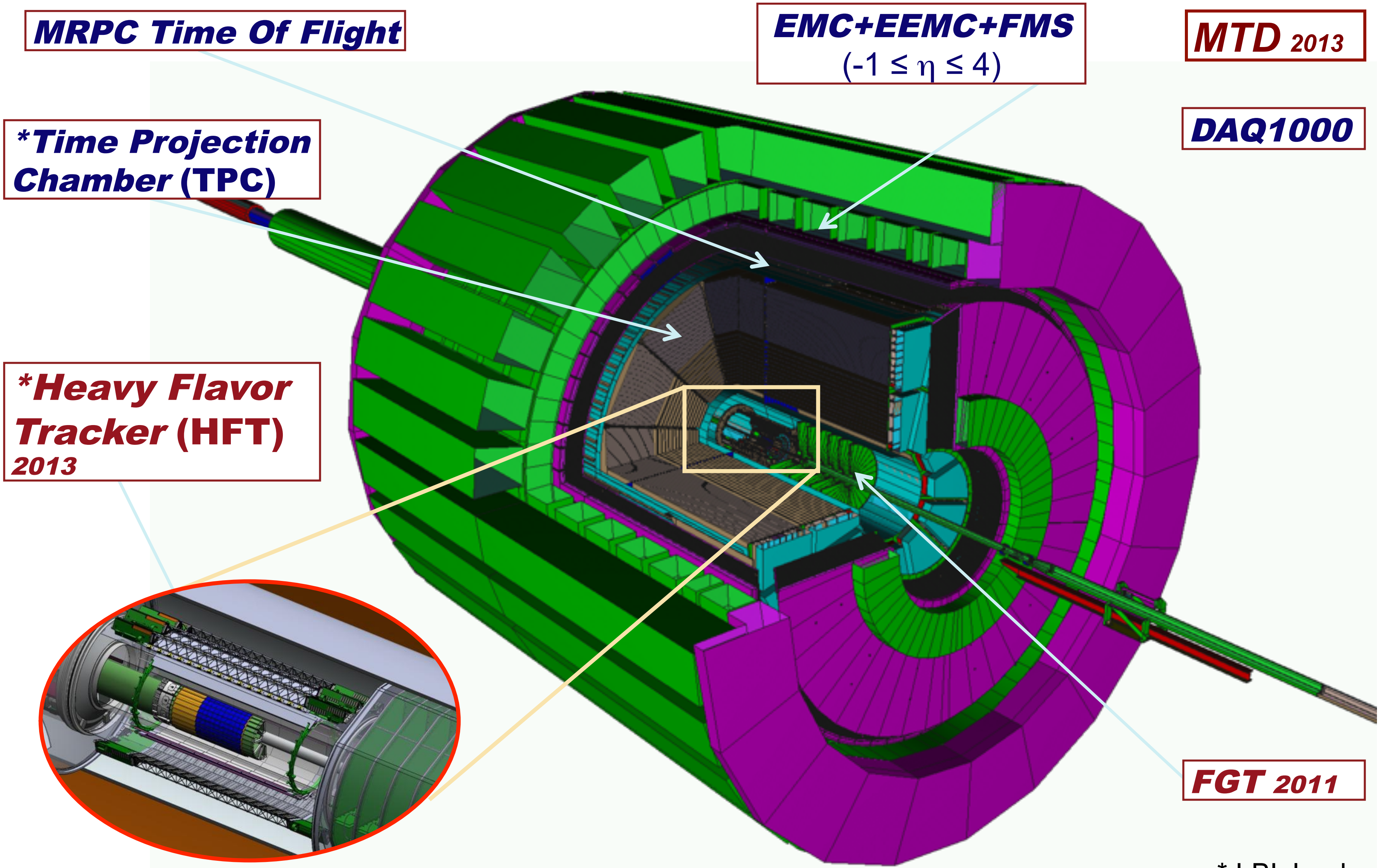
Fundamental Science: particle physics, nuclear physics, astrophysics, cosmology, …

State of Art Technology: detector R&D, simulations, IT, computing, mass/fast data managing, …

- 550 scientists
- 53 institutes
- 12 countries
~ 150 PhD thesis completed since 2001

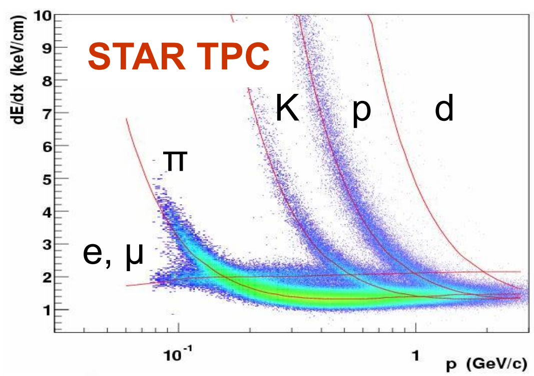


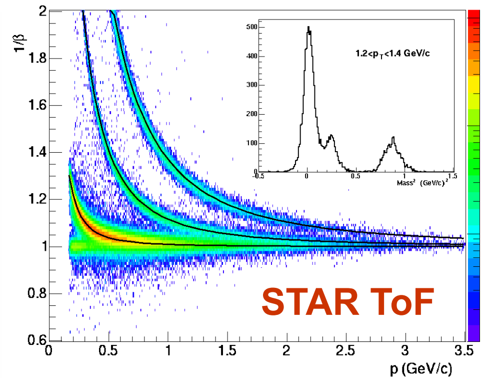
STAR Detectors *Fast and Full azimuthal particle identification*

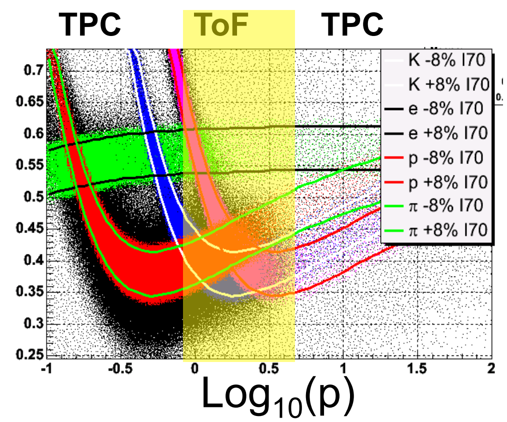


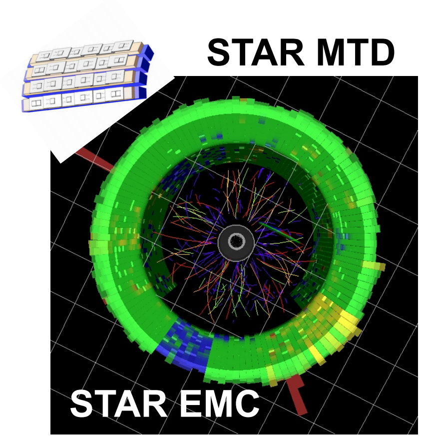
* LBL leads

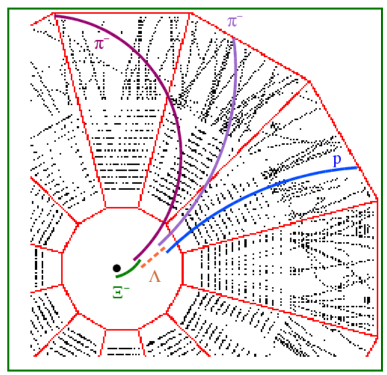
Particle Identification at STAR

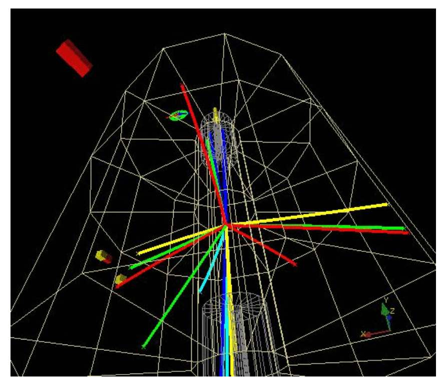


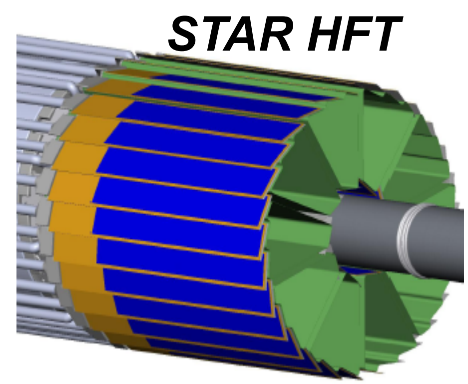








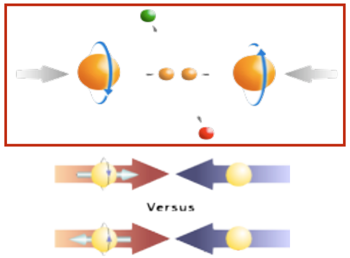


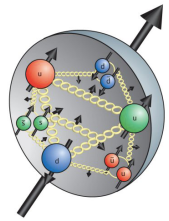


Neutral particles **Strange hyperons** **Jets** **Heavy Quark Hadrons**

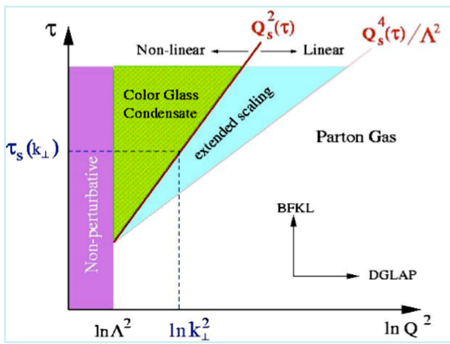
Multiple-fold correlations for both HI and Spin physics!

RHIC Physics Focus



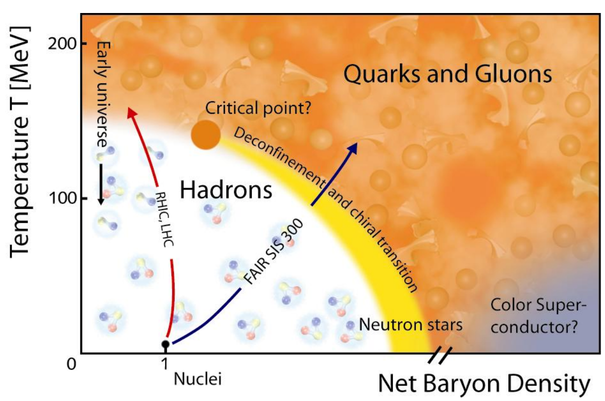


Polarized *p+p* program
- Study ***proton intrinsic properties***



Forward program
- Study low-x properties, initial condition, search for ***CGC***
- Study elastic and inelastic processes in pp2pp

2020 -
eRHIC
(eSTAR)



1) At 200 GeV at RHIC
- Study ***medium properties, EoS***
- pQCD in hot and dense medium

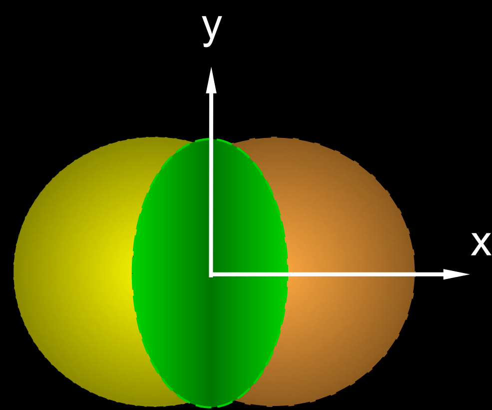
2) RHIC beam energy scan (BES)
- Search for the ***QCD critical point***
- Chiral symmetry restoration

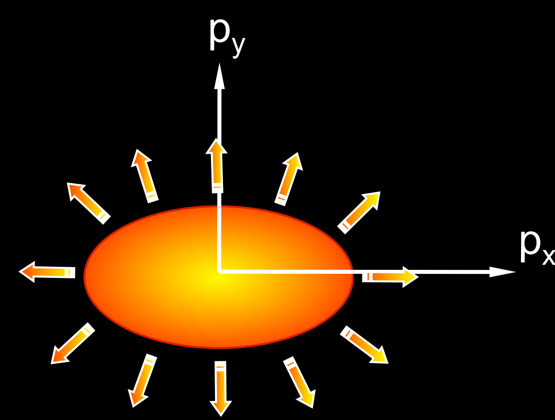
2) New Form of Matter at RHIC

- Partonic collectivity of the medium
- Anti-matter formation

Anisotropy Parameter v_2

coordinate-space-anisotropy ⇨ momentum-space-anisotropy

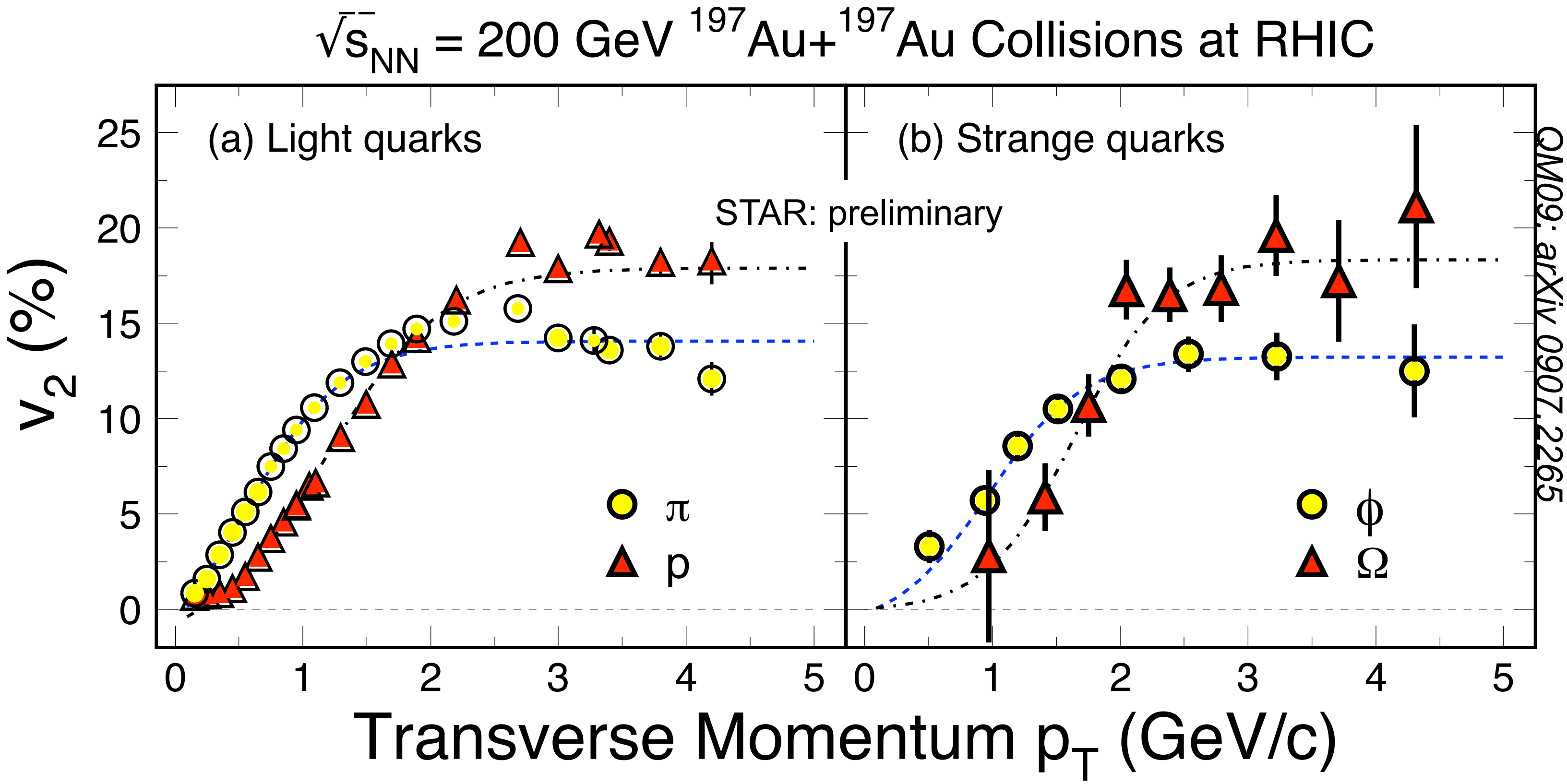




$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \qquad v_2 = \langle \cos 2\varphi \rangle, \;\; \varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

Initial/final conditions, EoS, degrees of freedom

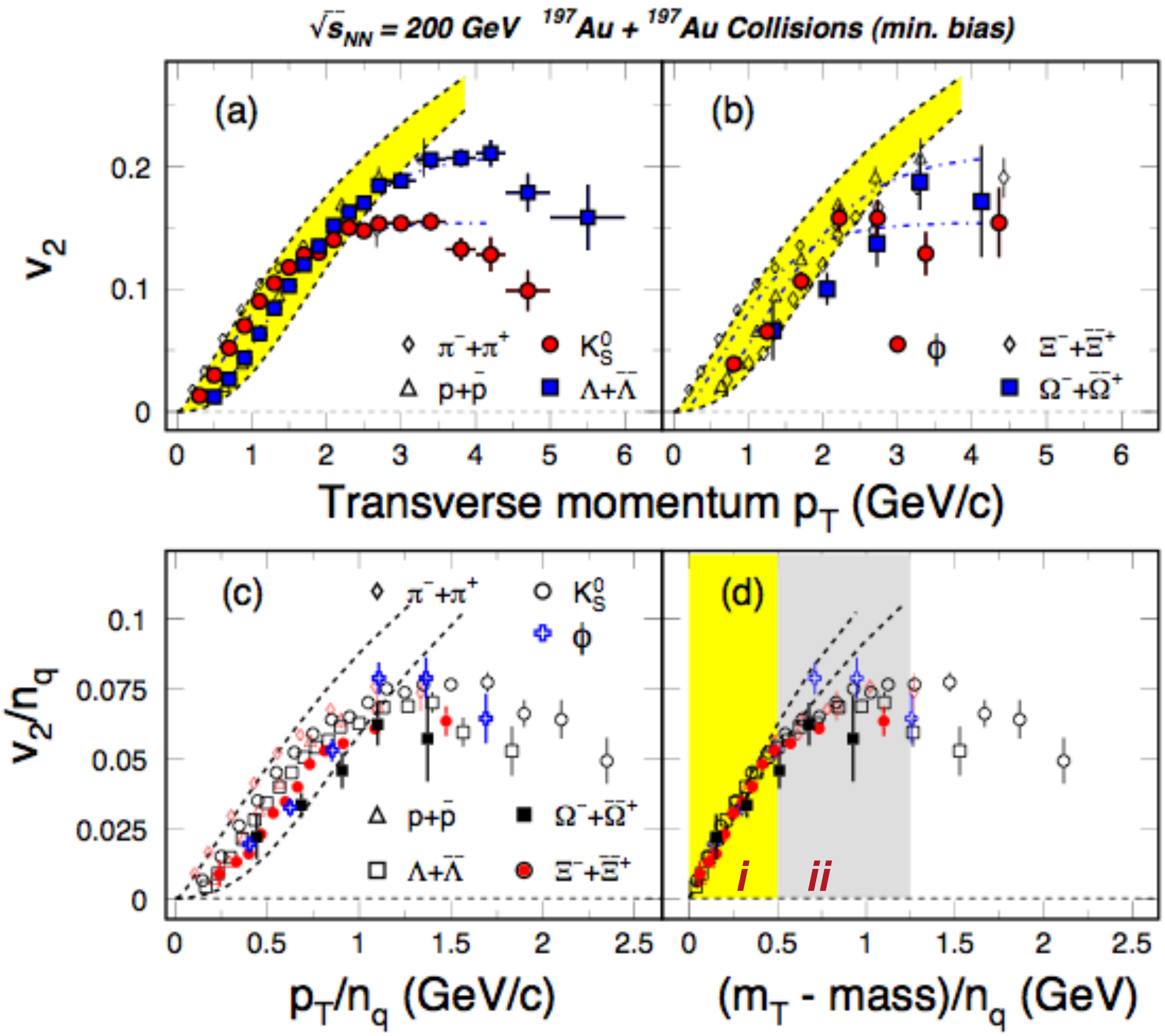
Partonic Collectivity at RHIC



Low p_T ($\leq$ 2 GeV/c): hydrodynamic mass ordering
High p_T (> 2 GeV/c): ***number of quarks scaling***

➔ ***Partonic Collectivity, necessary for QGP!***
➔ ***De-confinement in Au+Au collisions at RHIC!***

Collectivity, Deconfinement at RHIC



- v_2 of light hadrons and multi-strange hadrons
- scaling by the number of quarks

At RHIC:

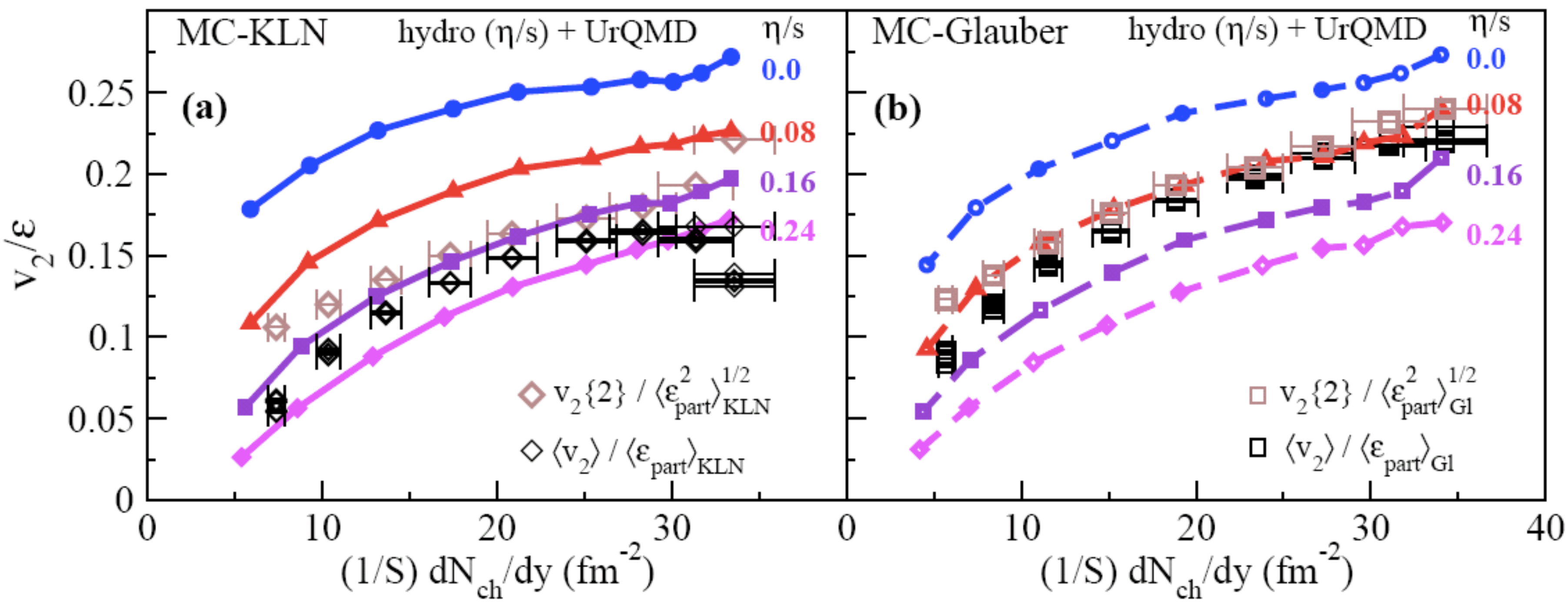
➪ **m_T - NQ scaling**

➪ **De-confinement**

*PHENIX: PRL**91**, 182301(03)*
*STAR: PRL**92**, 052302(04), **95**, 122301(05) nucl-ex/0405022, QM05*

S. Voloshin, NPA715, 379(03)
*Models: Greco et al, PR**C68**, 034904(03)*
Chen, Ko, nucl-th/0602025
*Nonaka et al. **PLB583**, 73(04)*
*X. Dong, et al., Phys. Lett. **B597**, 328(04).*
….

Comparison with Model Results

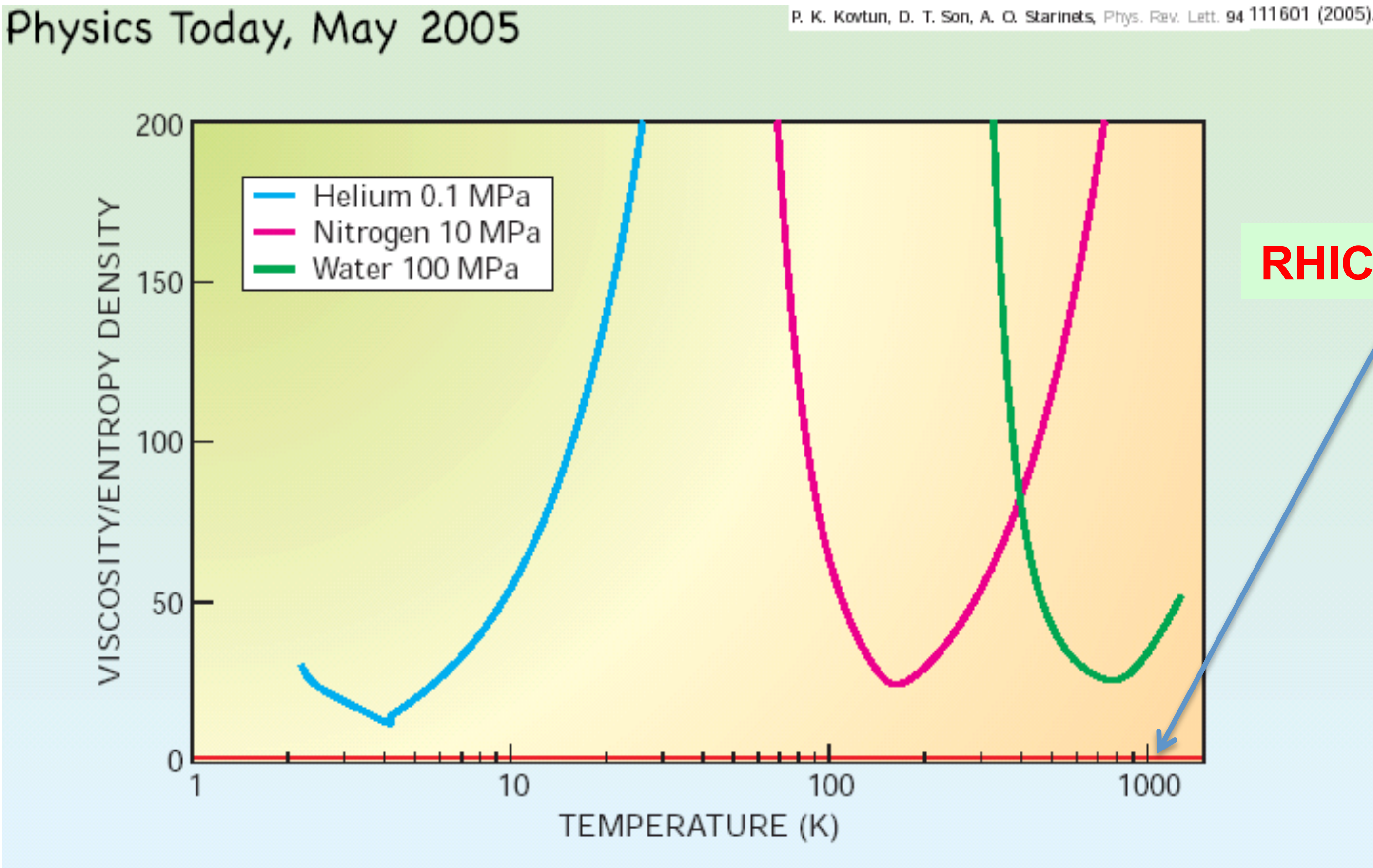


➔ ***Small value*** of specific viscosity over entropy ***η/s***

➔ Model uncertainty dominated by ***initial eccentricity ε***

Model: Song *et al. arXiv:1011.2783*

Low *η/s* for QCD Matter at RHIC



1) ***η/s* ≥ 1/4π**

2) ***η/s***(QCD matter) << ***η/s***(QED matter)

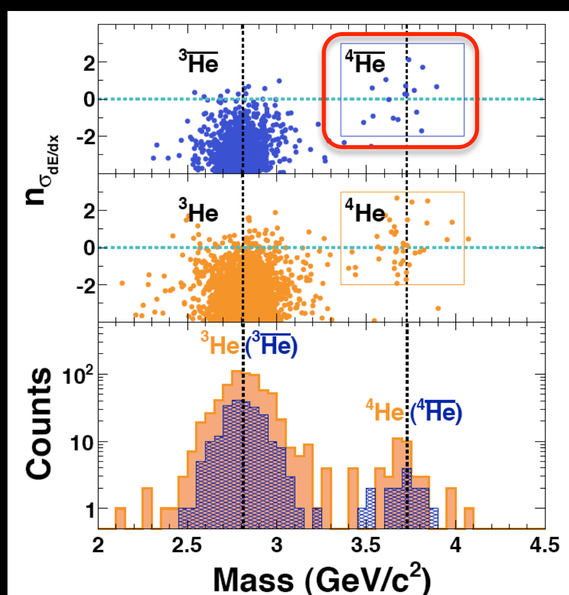
Antimatter Discoveries at RHIC

nature April, 2011

"Observation of the Antimatter Helium-4 Nucleus"

*by **STAR Collaboration***

***Nature**, 473, 353(2011).*

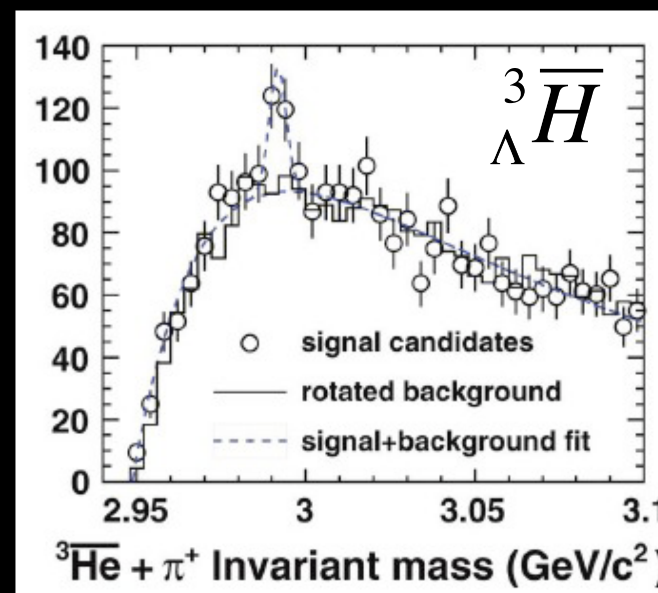


Science March, 2010

"Observation of an Antimatter Hypernucleus"

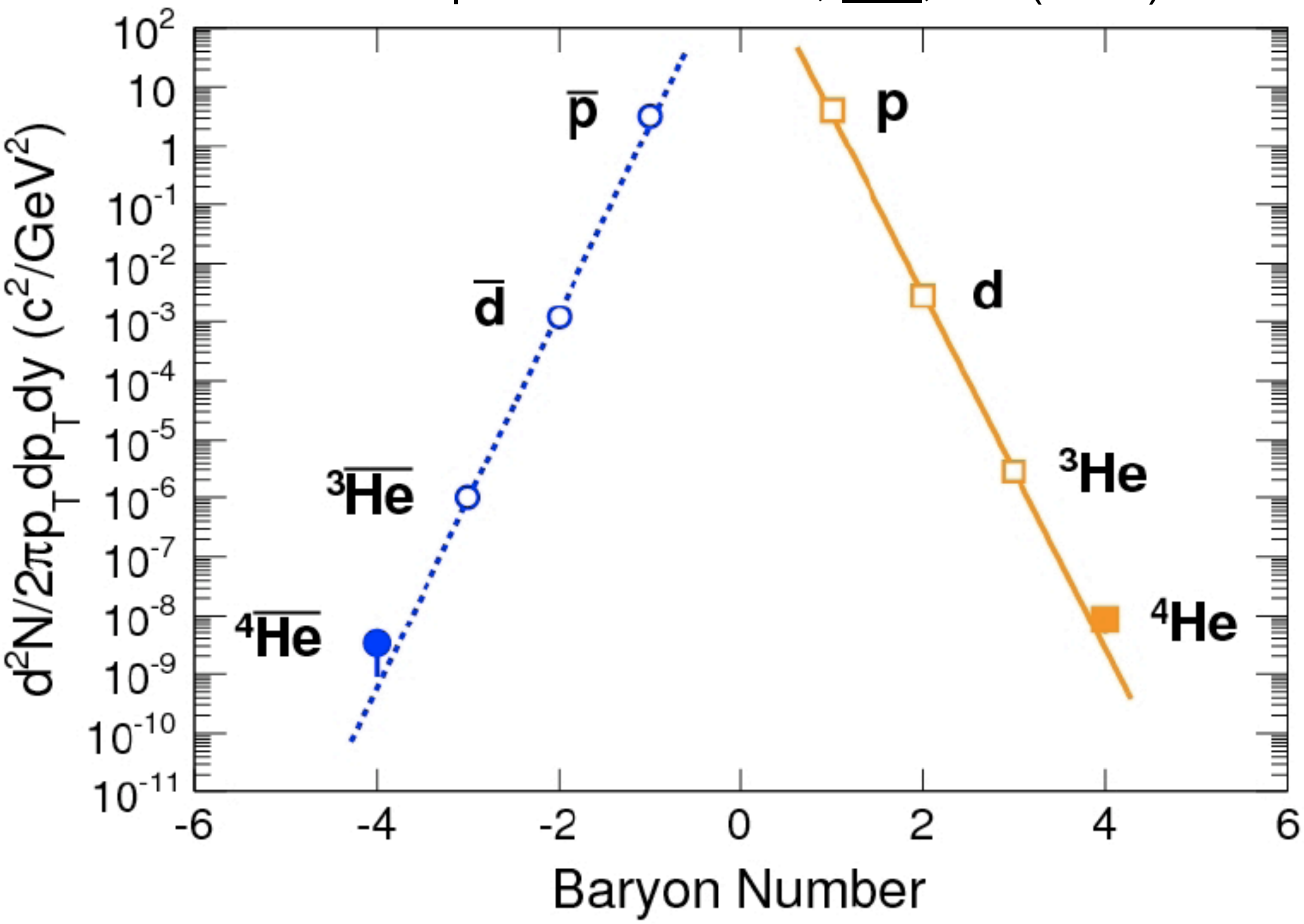
*by **STAR Collaboration***

***Science**, 328, 58(2010).*



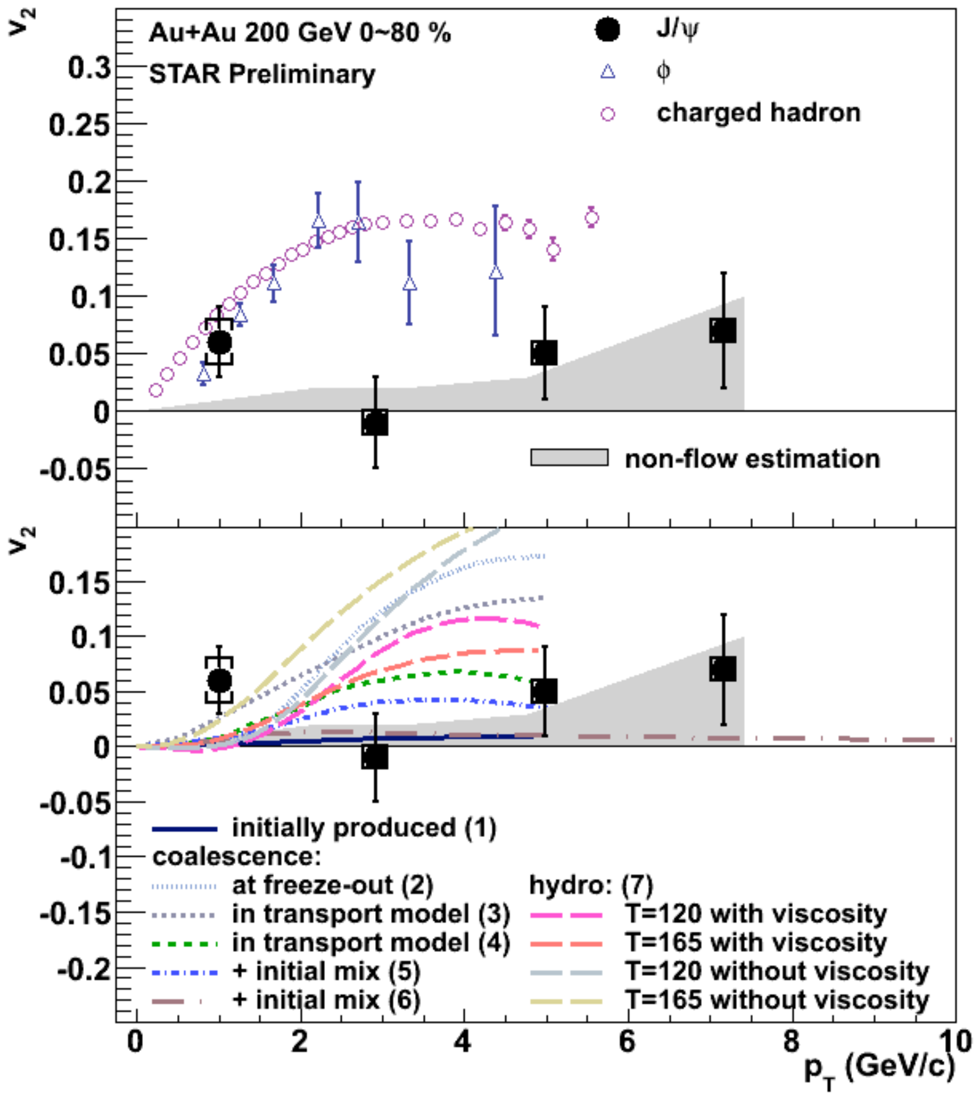
Light Nuclei Productions at RHIC

STAR Experiment: ***Nature***, **473**, 353(2011)



1) In high-energy nuclear collisions, **N(d) >> N(α)**:
   QGP ➔ (anti)light nuclei via coalescence
2) In the Universe, **N(d) << N(α): N(anti-α)?**

J/ψ v_2 Results



(1) High statistics results

(2) The value of v_2 for J/ψ is small

(3) At RHIC, collectivity for charm quark is not as strong as light ***u, d, s****-quark*

(4) STAR upgrade 'Heavy Flavor Track':

Summary I:

sQGP formed at Au+Au Collisions at 200 GeV

(1) In high-energy nuclear collisions, hot and dense ***matter,*** with ***partonic degrees of*** **freedom** and **collectivity,** has been formed

(2) The matter behavior like a ***quantum liquid*** with small ***η/s***

(3) Partonic matter ➔ **antimatter**: ${}^{3}_{\Lambda}\overline{H}$, ${}^{4}\overline{He}$

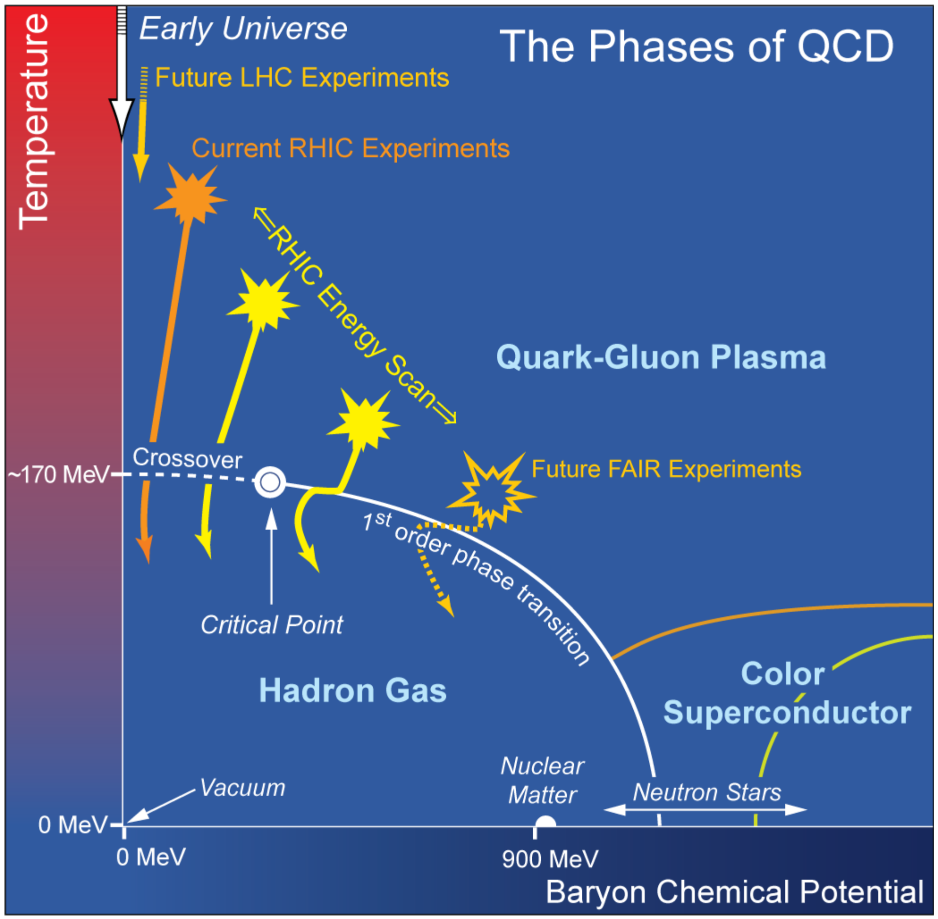
What is the structure of the QCD matter?

3) RHIC Beam Energy Scan

- Phase boundary
- QCD critical point

Beam Energy Scan at RHIC

Study QCD Phase Structure
- Signals of phase boundary
- Signals for critical point



Observations:

(1) v_2 - NCQ scaling:
partonic vs. hadronic dof

(2) Dynamical correlations:
partonic vs. hadronic dof

(3) Azimuthally HBT:
1st order phase transition

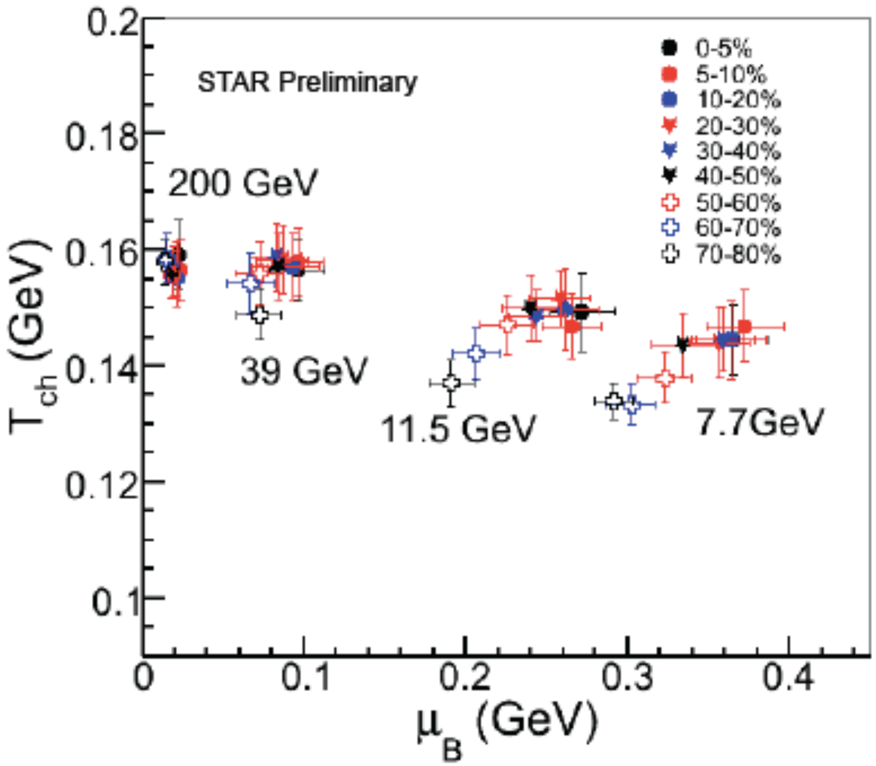
(4) Fluctuations:
Critical point, correl. length

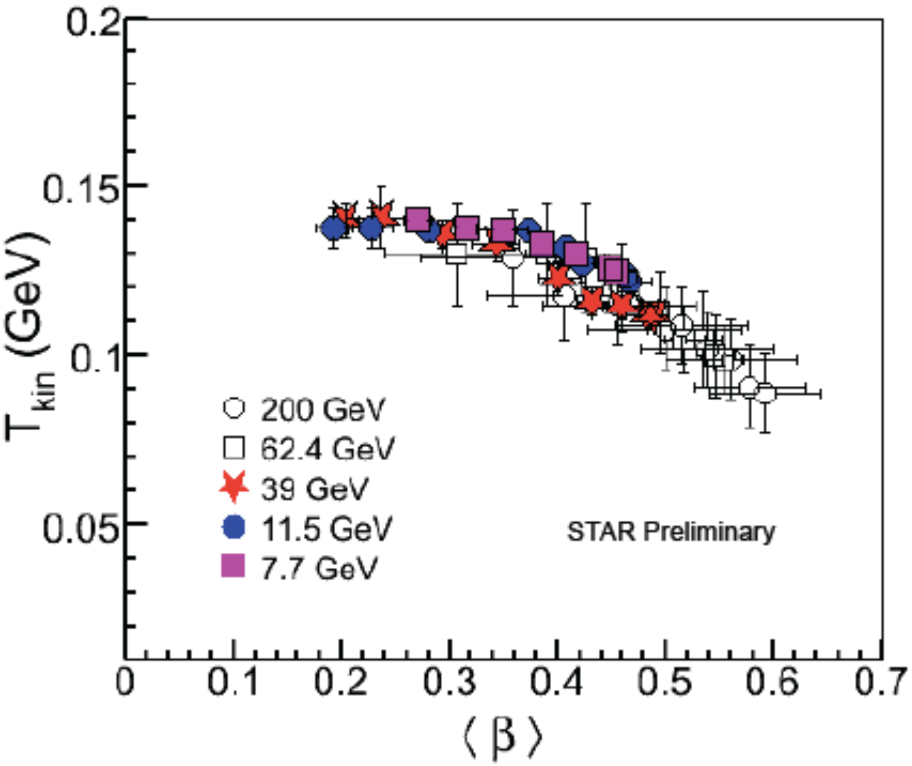
(5) Directed flow v_1
1st order phase transition

- *http://drupal.star.bnl.gov/STAR/starnotes/public/sn0493*

- *arXiv:1007.2613*

Bulk Properties at Freeze-out





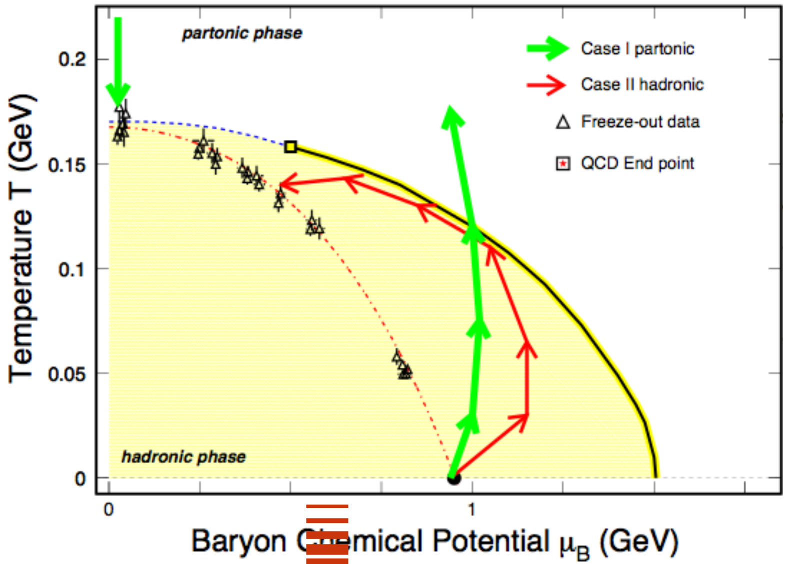
Chemical Freeze-out:

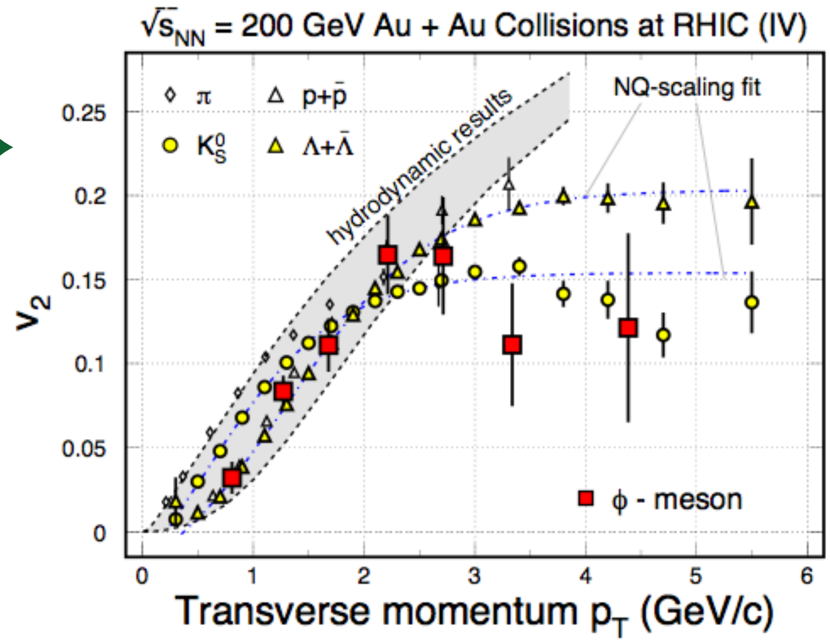
- Central collisions => higher values of T_{ch} and μ_B!
- The effect is stronger at lower energy.

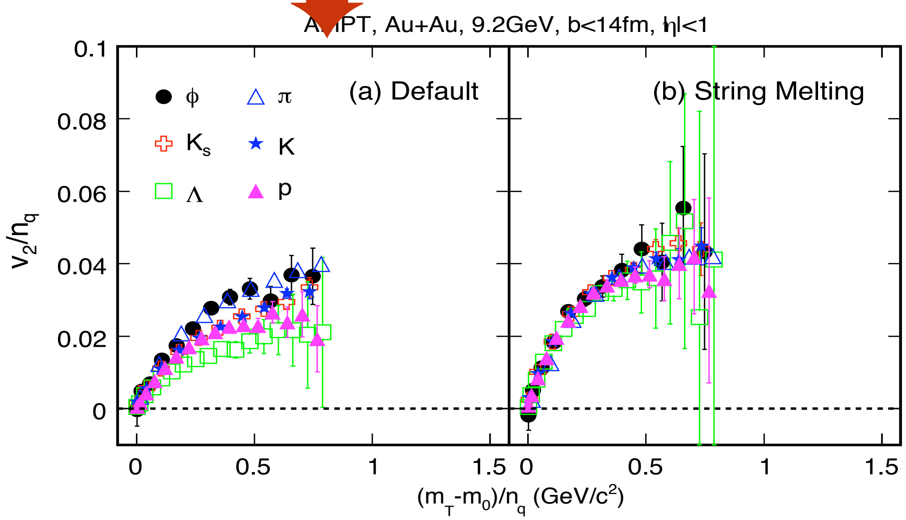
Kinetic Freeze-out:

- Central collisions => lower value of T_{kin} and larger collectivity β
- Little energy dependence.

Observable*: NCQ Scaling in v_2







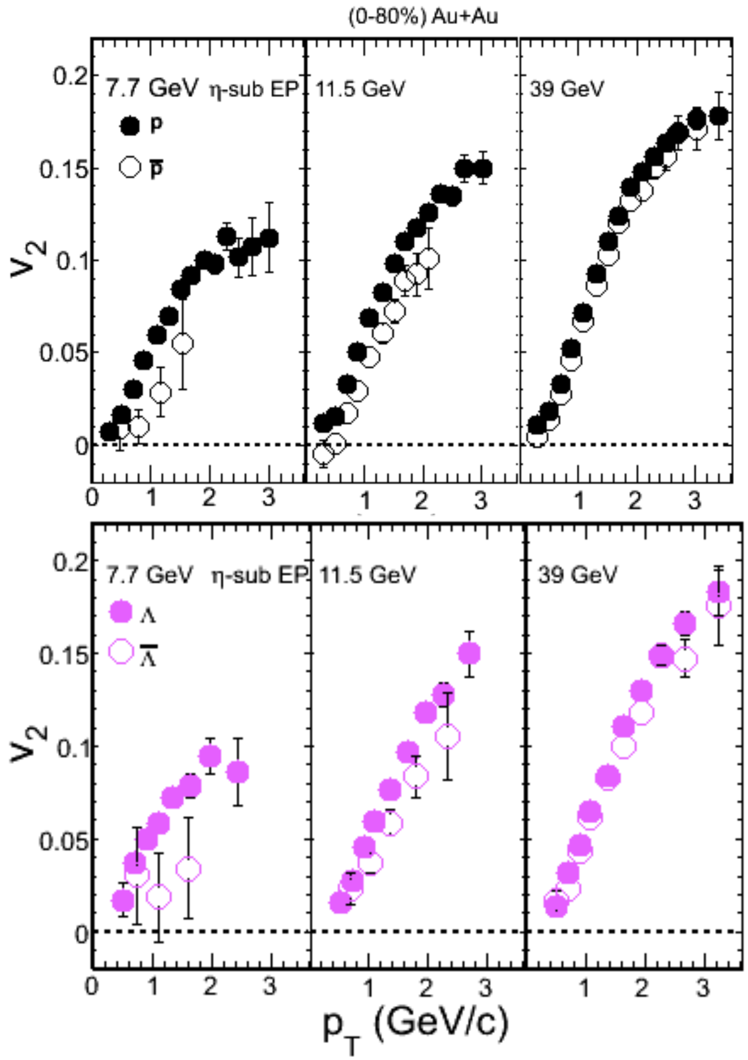
STAR Collaboration

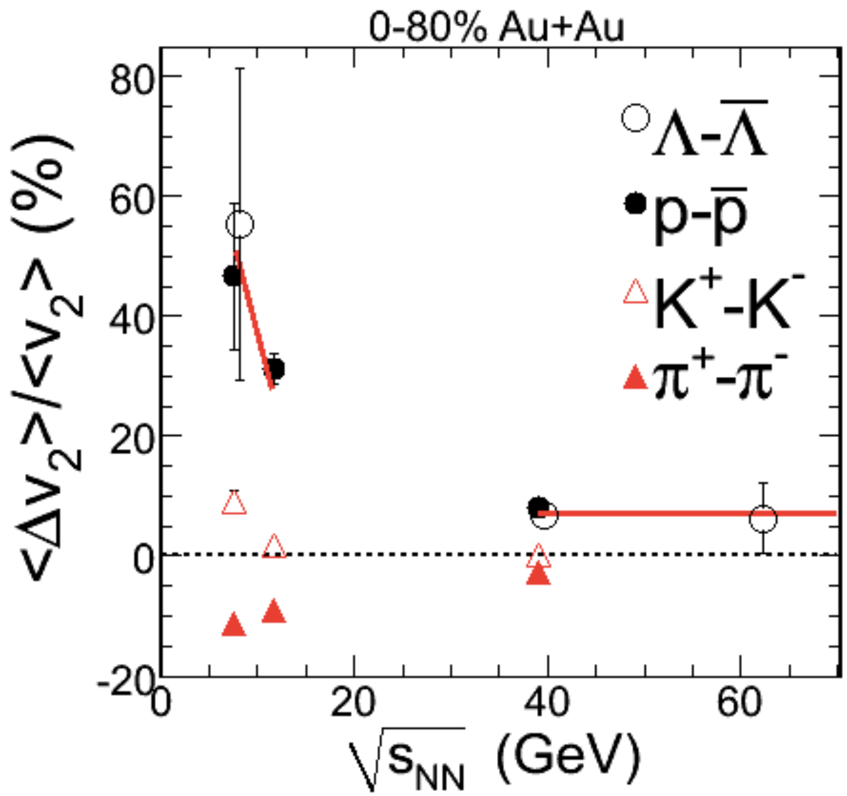
- $m_\phi \sim m_p \sim 1$ GeV
- ss ⇨ φ not K^+K^- ⇨ φ
- $\sigma_{\phi h} << \sigma_{p\pi,\ \pi\pi}$

In the hadronic case, no number of quark scaling and the value of v_2 of φ will be small.

*** Thermalization is assumed!**

Particle and Anti-particle v_2 vs. $\sqrt{s_{NN}}$



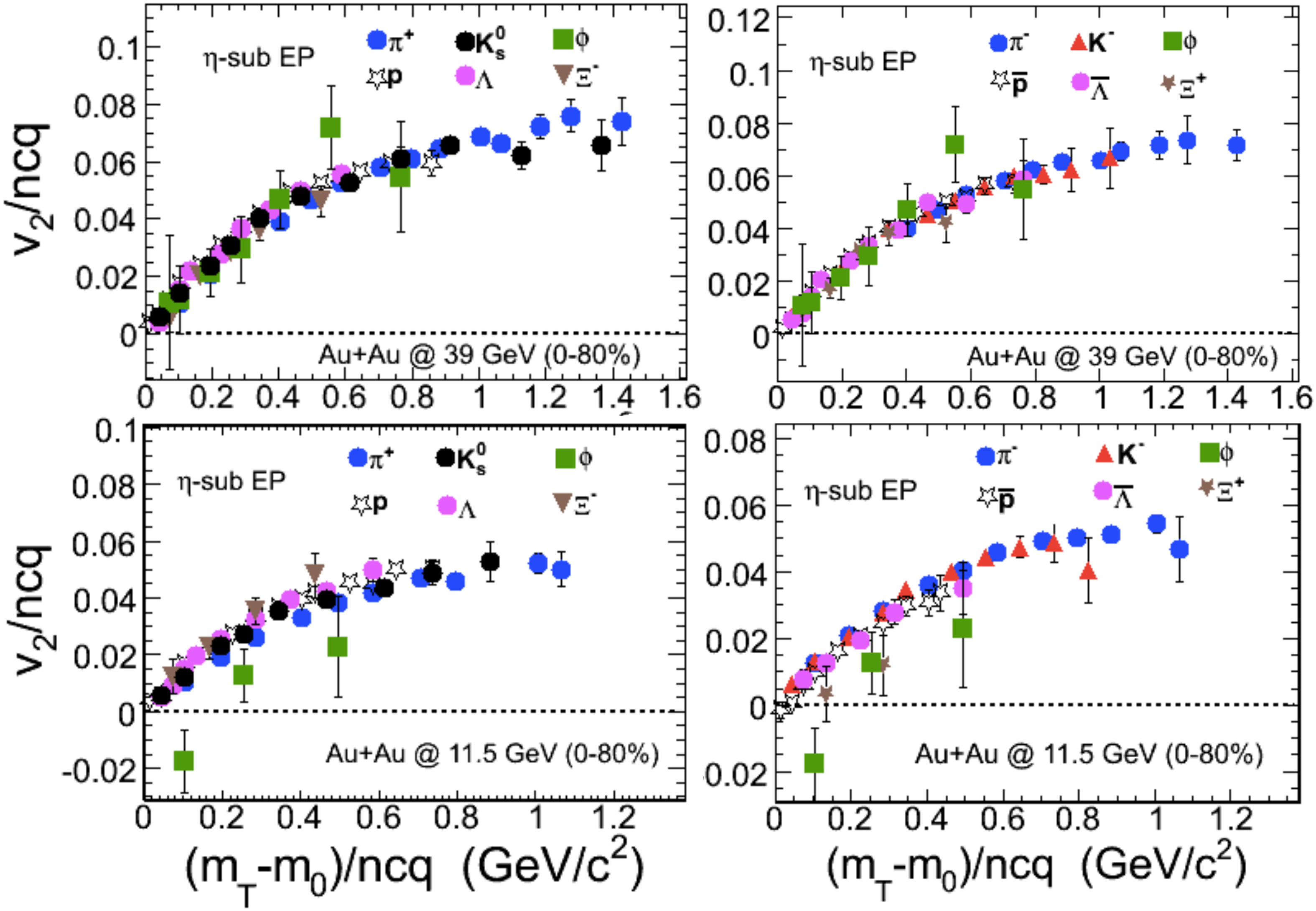


At $\sqrt{s_{NN}} \leq$ *11.5 GeV:*
- v_2(baryon) > v_2(anti-baryon)
- v_2(π^+) < v_2(π^-)
- v_2(K^-) < v_2(K^+)

STAR: Quark Matter 2011

Hadronic interactions are dominant

ϕ-meson v_2



The φ v_2 falls off trend from other hadrons at 11.5 GeV

Summary II: NCQ-Scaling in v_2

1) Partonic collectivity in 200 GeV collisions

2) At $\sqrt{s_{NN}} \le 11.5$ *GeV*

- v_2(baryon) > v_2(anti-baryon)

➔ v_2-NCQ-scaling broken

➔ **[hadronic] ⌫ $\sqrt{s_{NN}} \le 11.5$ *GeV***

[partonic] ⌫ $\sqrt{s_{NN}} \ge 39$ *GeV*

Where is the critical point?

Susceptibilities and Moments

Thermodynamic function:

$$\frac{p}{T^4} = \frac{1}{\pi^2}\sum_i d_i (m_i/T)^2 K_2(m_i/T)\cosh[(B_i\mu_B + S_i\mu_S + Q_i\mu_Q)/T]$$

The susceptibility: $T^{n-4}\chi_q^{(n)} = \frac{1}{T^4}\frac{\partial^n}{\partial\left(\mu_q/T\right)^n}P\left(\frac{T}{T_C},\frac{\mu_q}{T}\right)\Big|_{T/T_C},\qquad q = B,Q,S$

Conserved Quantum Number

$$\chi_q^{(1)} = \frac{1}{VT^3}\left\langle \delta N_q\right\rangle$$

$$\chi_q^{(2)} = \frac{1}{VT^3}\left\langle \left(\delta N_q\right)^2\right\rangle$$

$$\chi_q^{(3)} = \frac{1}{VT^3}\left\langle \left(\delta N_q\right)^3\right\rangle$$

$$\chi_q^{(4)} = \frac{1}{VT^3}\left(\left\langle \left(\delta N_q\right)^4\right\rangle - 3\left\langle \left(\delta N_q\right)^2\right\rangle^2\right)$$

$$\frac{T^2\chi_q^{(4)}}{\chi_q^{(2)}} = \kappa\sigma^2$$

$$\frac{T\chi_q^{(3)}}{\chi_q^{(2)}} = S\sigma$$

Thermodynamic function ⇔ Susceptibility ⇔ Moments

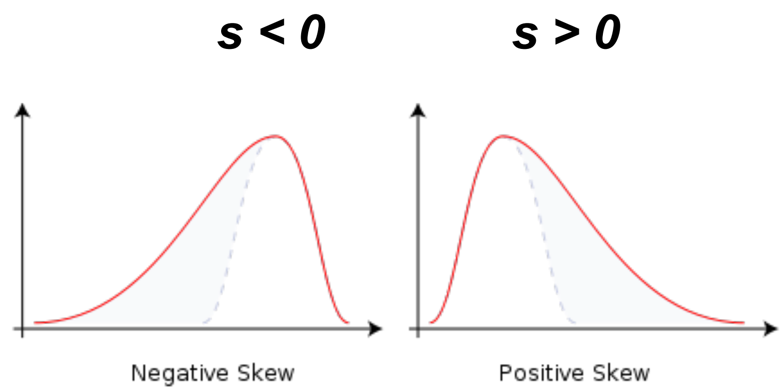
Model calculations, *e.g.* LGT, HRG ⇔ Measurements

Non-Gaussian Fluctuations

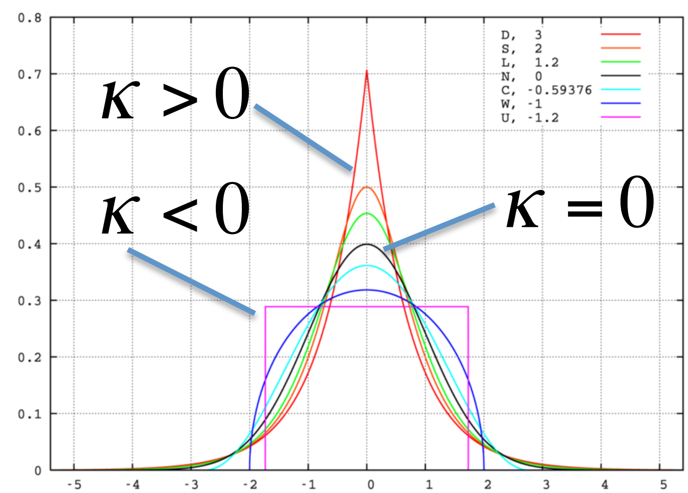
N: event by event multiplicity distribution

$$m = \langle N \rangle \qquad s = \frac{\left\langle \left(N - \langle N \rangle\right)^3 \right\rangle}{\sigma^3}$$

$$\sigma = \sqrt{\left\langle \left(N - \langle N \rangle\right)^2 \right\rangle} \qquad \kappa = \frac{\left\langle \left(N - \langle N \rangle\right)^4 \right\rangle}{\sigma^4} - 3$$



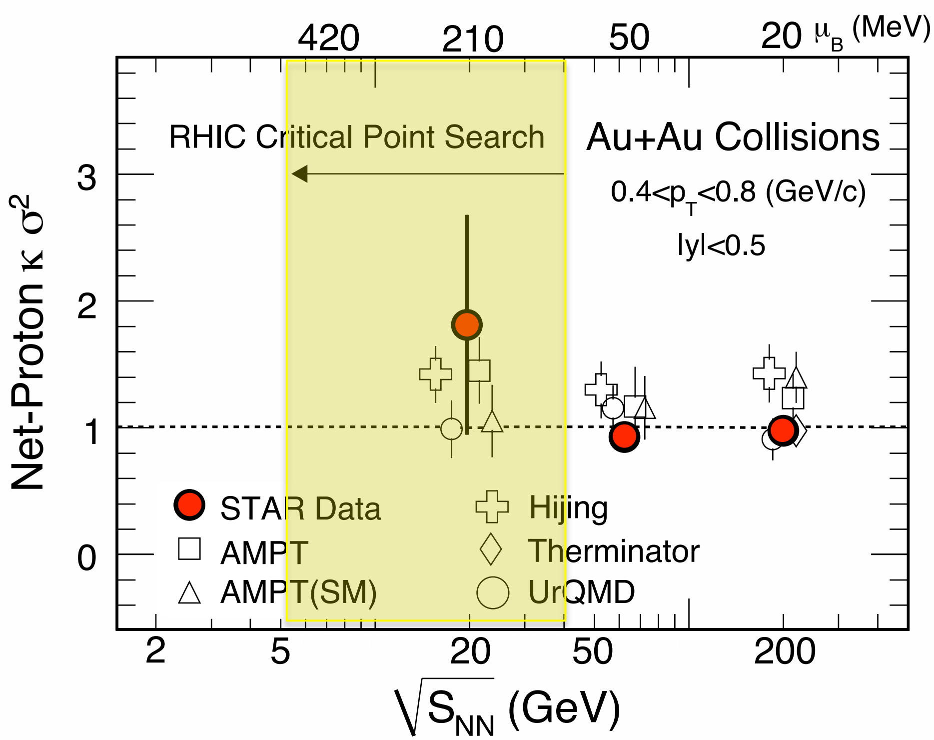
For a Gaussian distribution, the *s=0*, *κ=0.* **Ideal probe of the non-Gaussian fluctuations at critical point.**



Higher order correlations are correspond to higher power of the correlation length of the system: **more sensitive to critical phenomena**. Price: large number of events required.

First Results on High Moments

STAR: *PRL, **105**, 22302(2010)*



Energy Scan in Au+Au collisions:

Run 10: 7.7, 11.5, 39 GeV
Run 11: 19.6, 27 GeV

1) Centrality averaged events. In this analysis, effects of volume and detecting efficiencies are all canceled out.

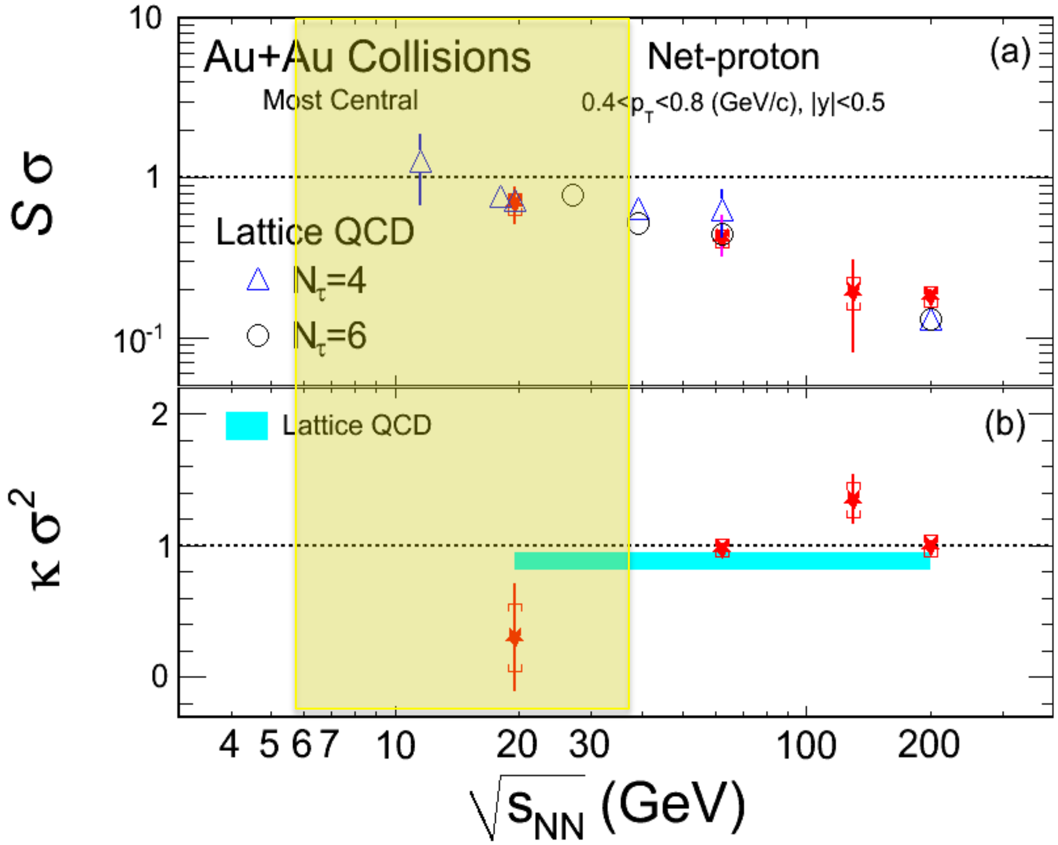
2) ALL transport model results values are higher than unity, except the Theminator result at 200GeV. LGT predicted values around 0.8-0.9, due to finite chemical potential effect.

3) Test of thermalization with higher moments.

4) **Critical point effect**: non-monotonic dependence on collision energy.

- STAR: PRL105, 22302(2010).
- F. Karsch and K. Redlich, arXiv:1007.2581

Comparing with LGT Results



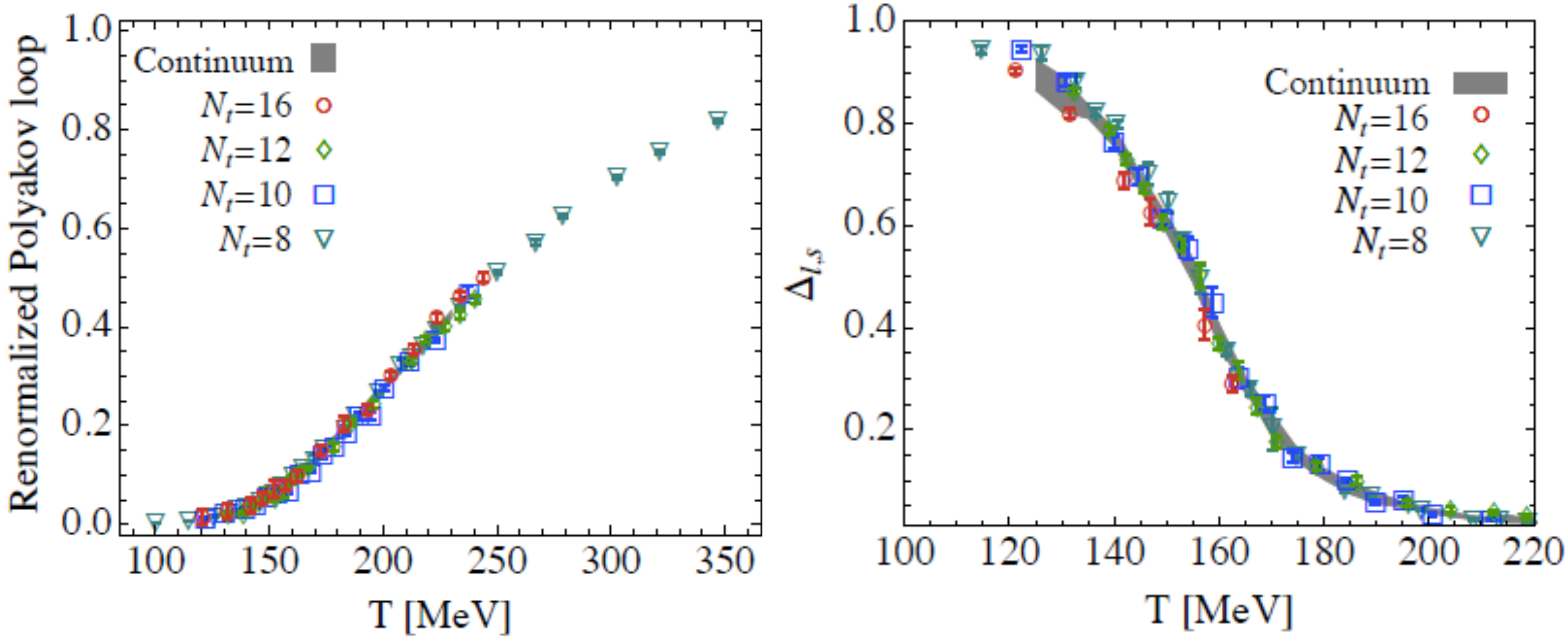
References:
- STAR, *PRL105, 22303(10)*
- **Gavai and Gupta: *PLB696, 459(11)***

Assumptions:

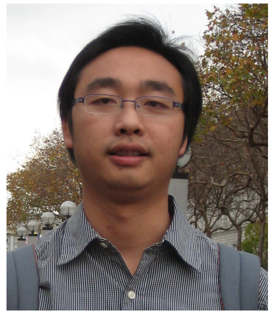
(a) Freeze-out temperature is close to LGT T_C
(b) Thermal equilibrium reached in central collisions
(c) Taylor expansions, at $\mu_B \neq 0$, on LGT results are valid

➔ **Lattice results are consistent with data for $60 < \sqrt{s_{NN}} < 200$ GeV**

Lattice: Phase Transition Temperature



Action	Temperature
Polyakov Loop	**T_C^{conf} ~ 170 MeV**
Chiral Operator	**T_C^{Chiral} ~ 160 MeV**
RHIC Data	**T_C^{Exp} ~ 175^{+1}_{-7} MeV**
	(T_{CH}^{Exp} ~ 160±5 MeV)

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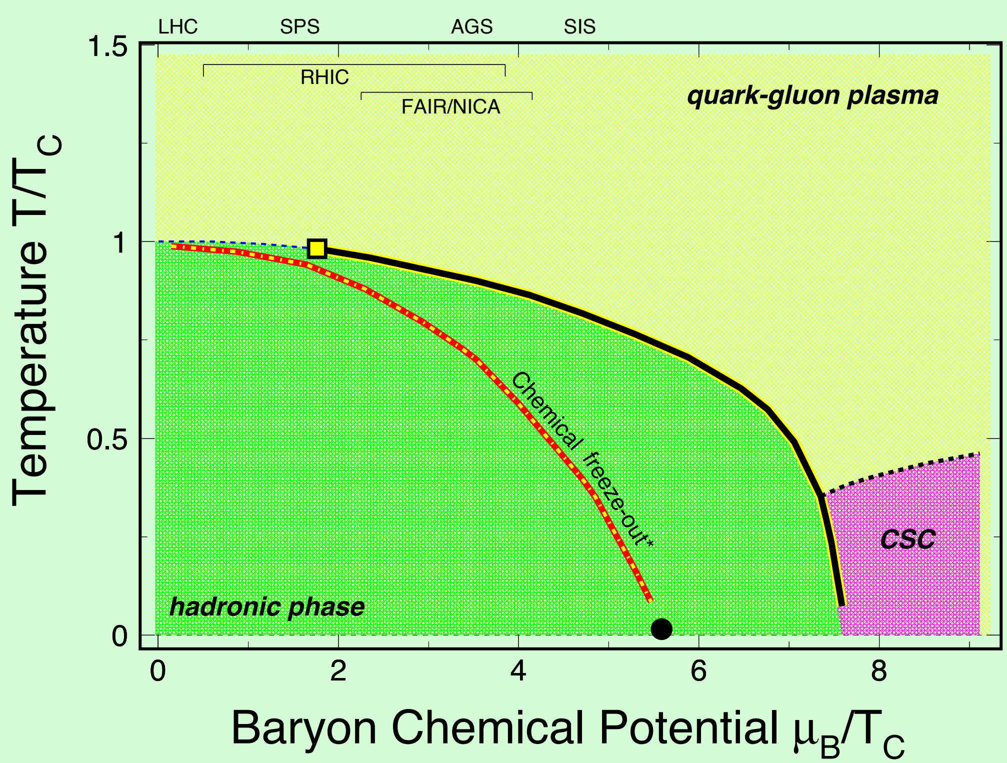
Sourendu Gupta, Xiaofeng Luo, Bedanga Mohanty, Hans-George Ritter, NX,
Science, *332, 1525(2011).*



June, 2011

"Scale for the Phase Diagram of Quantum Chromodynamics"

$\boldsymbol{T_c = 175^{+1}_{-7}}$ (MeV)

Science, 332, 1525(2011)

Summary

(1) In high-energy nuclear collisions, hot and dense ***matter, with partonic degrees of*** **freedom and collectivity, has been formed**

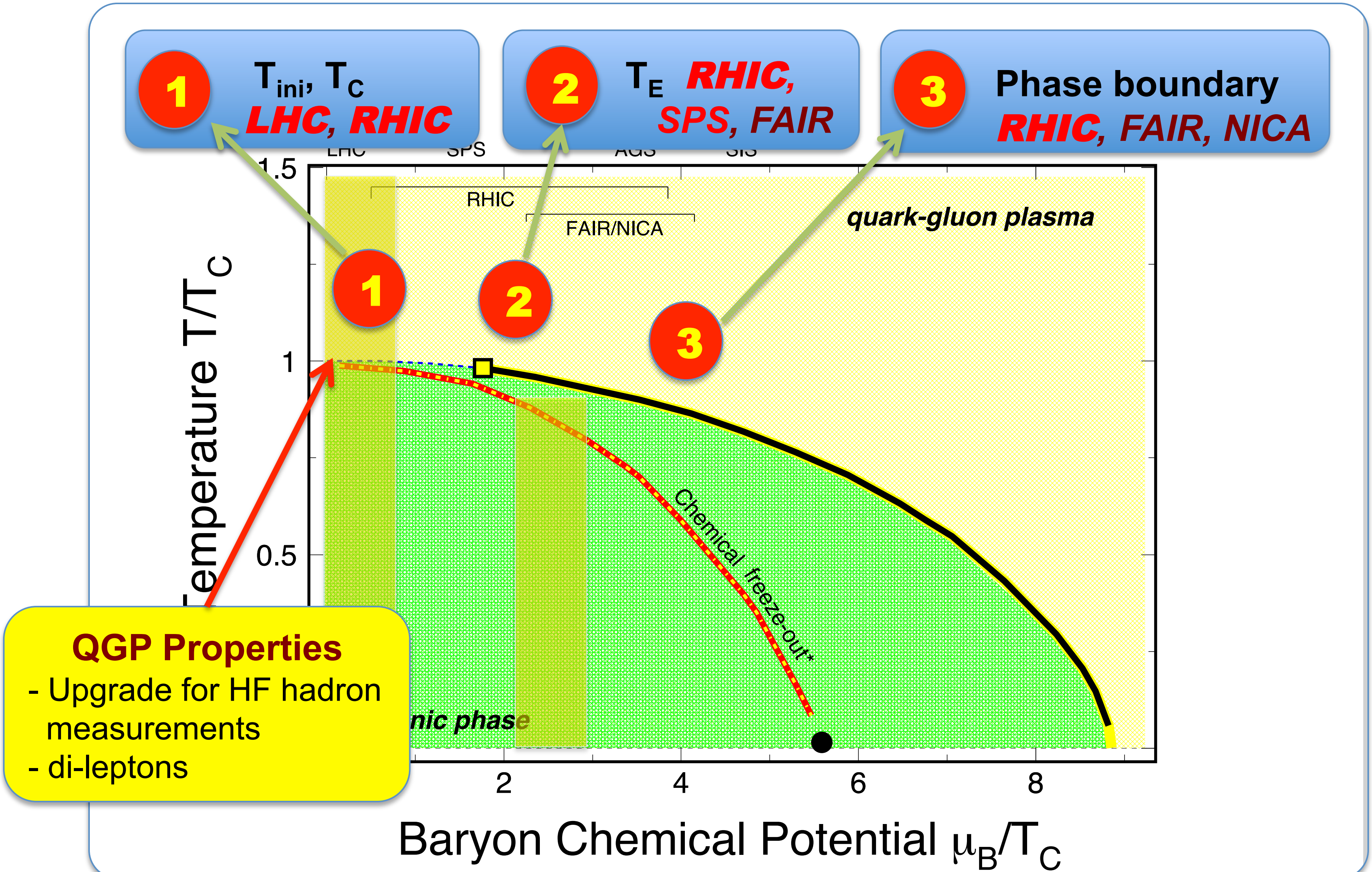
(2) The matter behavior like a ***quantum liquid with*** small ***η/s***

(3) Partonic matter ➔ **antimatter**: ${}^{3}_{\Lambda}\overline{H}$, ${}^{4}\overline{He}$

(4) **[partonic] < μ_B *~110–320* (MeV) < [hadronic]**

(5) Net-proton distributions are consistent with LGT results. QCD Scale: ***T_C=175$^{+1}_{-7}$* (MeV)**

Outlook: (7.7, 11.5, 15.5, 19.6, 27, 39,62, 200 GeV)



Summary and Outlook

1) **STAR at RHIC**: Dedicated facility for studying matter with QCD degrees of freedom:

- Properties of QGP

- Sea quark and gluon contributions to proton helicity structure

- QCD critical point, phase boundary

2) Future: EIC (eRHIC, 2022 - …)

- Partonic structures of nucleon and nuclei

- Dynamical evolution from cold nuclear matter to hot QGP

Phase Structures of QCD Matter